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Natural Suppression of FCNC and CP Violating Effects**

R.N. Mohapatra and A. Riotto

*Fermi National Accelerator Laboratory  
P.O. Box 500, Batavia, Illinois 60510*

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# Anomalous $U(1)$ Mediated SUSY Breaking, Fermion Masses and Natural Suppression of FCNC and CP Violating Effects

R.N. Mohapatra<sup>(1)\*</sup> and A. Riotto<sup>(2)†</sup>,

<sup>(1)</sup>*Department of Physics and Astronomy, University of Maryland,  
College Park, MD 20742, USA*

<sup>(2)</sup>*NASA/Fermilab Astrophysics Center,  
Fermi National Accelerator Laboratory,  
Batavia, Illinois 60510-0500, USA*

## Abstract

We construct realistic supergravity models where supersymmetry breaking arises from the  $D$ -terms of an anomalous  $U(1)$  gauge symmetry broken at the Planck scale. The model has the attractive feature that the gaugino masses, the  $A$  and  $B$  terms and the mass splittings between the like-charged squarks of the first two generations compared to their average masses are all suppressed. As a result, the electric dipole moment of the neutron as well as the flavor changing neutral current effects are predicted to be naturally small. These models predict naturally the expected value of the  $\mu$ -term and also have the potential to qualitatively explain the observed mass hierarchy among quarks and leptons.

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\*Electronic address: [rmohapatra@umdhep.umd.edu](mailto:rmohapatra@umdhep.umd.edu)

†Electronic address: [riotto@fnal.gov](mailto:riotto@fnal.gov)

Supersymmetric extensions of the standard model (MSSM) have been the focus of intense theoretical activity due to the fact that they provide a natural solution to the problem of stability of the weak scale under quantum corrections [1]. Since experimental observations require supersymmetry to be broken, it is essential to have a knowledge of the nature and the scale of supersymmetry breaking in order to have a complete understanding of the physical implications of these models. At the moment, we lack such an understanding and therefore it is important to analyse the various ways that supersymmetry breaking can arise and study their consequences, in the hope that one can gain some insight into this problem. There are however several hints from the study of general class of MSSM which could perhaps be useful in such a discussion. Two particular ones that rely on the supersymmetric sector of model are: (i) natural suppression of flavor changing neutral currents (FCNC) which require a high degree of degeneracy among squarks of different flavor and (ii) stringent upper limits on the electric dipole moment of the neutron (NEDM) which imply constraints on the gaugino masses as well as on the  $A$  and  $B$  terms of MSSM [2]. In this letter we take the point of view that the above conclusions may be telling us something about the nature of supersymmetry breaking. If this is true, then it is important to isolate those SUSY breaking scenarios which realize the above properties in a simple manner and study their implications. It has been already pointed out that the recently discussed gauge mediated SUSY breaking models [3] seem to have these properties. In this letter, we study another class of models with the same property and analyse its consequences.

An important ingredient of the models, we are interested in, is the existence of an anomalous  $U(1)$  gauge symmetry whose linear  $D$ -term combined with an appropriate superpotential for the hidden sector fields leads to supersymmetry breaking. This SUSY breaking is fed down to the visible sector [4] both by the  $D$ -term as well as by the supergravity effects. It was shown in Ref. [4] that in the resulting theory, the gaugino

masses are suppressed. It was also conjectured in Ref. [4] that the FCNC and CP violating effects in these models are suppressed. In this paper, we construct full realistic versions of this model, which have the feature that relative squark mass difference (between the like-charged squarks of the first two generations)  $\delta_q \equiv \Delta m_q^2/m_q^2$ , the gaugino masses relative to the average squark masses  $\delta_\lambda \equiv m_\lambda/m_{\bar{q}}$  as well as  $\mu/m_{\bar{q}}$  and  $A/m_{\bar{q}}$  are all small, with the suppression characterized by a common parameter  $\epsilon \simeq 10^{-2}$ . This leads to the desirable property that FCNC effects and SUSY CP effects in the electric dipole moment,  $d_n^e$  of the neutron are suppressed to an acceptable level. The suppression of  $d_n^e$  is also due to the factor  $\epsilon$  unlike in Ref. [4]. Keeping the above properties, we construct two models, which differ in the way the electroweak symmetry breaking arises and the qualitative pattern of fermion masses is predicted. In the first model, the electroweak symmetry breaking arises at the tree level whereas in the second one, it arises purely out of radiative corrections as in the usual supergravity models. Furthermore the first model has the property th the down quark and charged lepton masses are much smaller than the up quark masses of the corresponding generation whereas in the second one, the quark mass hierarchy is in more detailed qualitative agreement with observations. Let us briefly outline the first model before proceeding to extract its implications for the MSSM and illustrate how the afore-mentioned properties common to both the models emerge. At the end, we discuss the second model, which shares all the properties with the first model except the prediction for the fermion mass hierarchies and the way the electroweak symmetry breaking is induced.

As already alluded to, the crucial feature of the model is the existence of a  $U(1)$  gauge group, which is anomalous. The  $U(1)$  group may be assumed to emerge from string theories. We will assume that the anomaly is cancelled by the Green-Schwarz mechanism. Since the  $U(1)$  is anomalous, i.e.  $\text{Tr} \mathbf{Q} \neq 0$ , a Fayet-Illiopoulos term which is a linear  $D$ -term is always generated as a quantum effect. We further assume that there

is a pair of hidden sector fields denoted by  $\phi_+$  and  $\phi_-$  which have  $U(1)$  charges  $+1$  and  $-1$  respectively and that the fields of the standard model also carry  $U(1)$  charges. It is the assignment of the  $U(1)$  charges to quark superfields that help in the solution of the FCNC and CP problems and in qualitatively explaining the fermion mass hierarchy. We will illustrate the technique with the help of two models. In the first one, the left-handed quark and lepton doublets  $Q, L$  are all assumed to have the  $U(1)$  charge  $q$  and the singlet fields  $u^c, d^c$  and  $e^c$  have charge  $q'$ ; the two Higgs fields of MSSM,  $H_u$  and  $H_d$  are assumed to have  $U(1)$  charges  $-q - q'$  and  $1 + q + q'$  respectively. We will show that demanding that the superpotential lead to  $QH_d d^c$  type terms fixes the value of  $q + q'$ . Note that both the superpotential  $W$  and the Kahler potential  $K$  of the model must be invariant under the anomalous  $U(1)$  symmetry. The superpotential is  $W = W_0 + W_1 + W_2$ , where

$$\begin{aligned}
W_0 &= m\phi_+\phi_-, \\
W_1 &= h_u Q H_u u^c, \\
W_2 &= (h_d Q H_d d^c + h_e L H_d e^c) \frac{\phi_-^2}{M_{P\ell}^2} \\
&\quad + Q H_u u^c \frac{\phi_+\phi_-}{M_{P\ell}^2} + \dots.
\end{aligned} \tag{1}$$

In the above equation, the ellipses denote all other higher dimensional terms allowed by the gauge symmetry and, as we will see below, make very small contributions to the effects isolated below. The first term in  $W_2$  fixes  $q + q' = 1/2$ . In what follows we will consider the assignment where  $q = q' = 1/4$ . The parameter  $m$  is chosen to be of the order of the weak scale.

Let us now write down the Kahler potential  $K(z_i, z_i^*)$  for the fields of the model generically indicated by  $z_i$ . It can be written as the sum of two terms: one that involves the bilinear terms of the form  $z_i^* z_i$  and a second piece that involves mixed terms which are strongly constrained by the  $U(1)$  symmetry.

$$\begin{aligned}
K &= K_0 + K_1, \\
K_0 &= \sum_i |z_i|^2, \\
K_1 &= \lambda H_u H_d \frac{\phi_+^\dagger}{M_{Pl}} + \text{h.c.} + \dots
\end{aligned} \tag{2}$$

In order to proceed further, we have to write down the potential of the model involving the scalar fields  $\phi_\pm$ ,  $H_u^0$ ,  $H_d^0$  and isolate the vacuum state. The part of the potential containing the  $\phi_-$  and  $\phi_+$  fields reads

$$\begin{aligned}
V &= m^2(|\phi_+|^2 + |\phi_-|^2) \\
&+ \frac{g^2}{2} \left( -\frac{1}{2}|H_u^0|^2 + \frac{3}{2}|H_d^0|^2 + |\phi_+|^2 - |\phi_-|^2 + \xi \right)^2.
\end{aligned} \tag{3}$$

Before discussing the minimization of the full potential, let us consider the part of  $V$  setting  $H_u^0 = H_d^0 = 0$ . It is easy to see that its minimum breaks supersymmetry as well as the anomalous  $U(1)$  gauge symmetry with [4]

$$\begin{aligned}
\langle \phi_- \rangle &= \left( \xi - \frac{m^2}{g^2} \right)^{1/2}, \quad \langle \phi_+ \rangle = 0 \\
\langle F_{\phi_+} \rangle &= m \left( \xi - \frac{m^2}{g^2} \right)^{1/2}.
\end{aligned} \tag{4}$$

If we parameterize  $\xi = \epsilon M_{Pl}^2$ , for  $m \ll M_{Pl}$ , we have  $\langle \phi_- \rangle \simeq \epsilon^{1/2} M_{Pl}$  and  $\langle F_{\phi_+} \rangle \simeq \epsilon^{1/2} m M_{Pl}$ . Assuming that  $\xi$ -term is induced by loop effects, one can estimate [4,5]  $\xi = \frac{g^2 \text{Tr} \mathbf{Q} M_{Pl}^2}{192\pi^2}$ , so that  $\epsilon$  can be assumed to be of order  $10^{-2}$ . It was pointed out in ref. [4] that the gaugino masses are generated in this model by superpotential terms of type  $\lambda' W^\alpha W_\alpha \left( \frac{\phi_+ \phi_-}{M_{Pl}^2} \right)$ . As a result, one gets gaugino masses to be  $m_{\lambda_g} = \lambda' \epsilon m$ .

From the  $K_1$  term in the Kahler potential supergravity effects induce a  $\mu$ -term by means of the Giudice-Masiero mechanism [6]. Indeed,  $K_1$  induces at low energy the operator

$$\lambda \int d^4\theta H_u H_d \frac{\phi_+^\dagger}{M_{Pl}}, \tag{5}$$

giving rise to a  $\mu$ -term, with  $\mu = \lambda\epsilon^{1/2}m$ . Notice that the corresponding  $B$ -term in the potential is not induced at order  $\epsilon$ , even though it will be generated by radiative corrections when running from the Planck scale down to the weak scale.

We integrate out the heavy field  $\phi_-$  to obtain the effective potential of the light fields. Minimization with respect to  $\phi_-$  gives

$$|\phi_-|^2 = \xi + |\phi_+|^2 - \frac{1}{2}|H_u^0|^2 + \frac{3}{2}|H_d^0|^2 - \frac{m^2}{g^2}. \quad (6)$$

The effective potential of the fields  $(\phi_+, H_d^0, H_u^0)$  is at the leading order in  $m^2/M_{P\ell}^2$

$$\begin{aligned} V &= 2m^2|\phi_+|^2 + m_{H_u}^2|H_u^0|^2 + m_{H_d}^2|H_d^0|^2 \\ &\quad - m_3^2(H_u^0 H_d^0 + \text{h.c.}) + D\text{-terms}, \\ m_{H_d}^2 &= |\mu|^2 + \frac{3}{2}m^2 + m_0^2, \\ m_{H_u}^2 &= |\mu|^2 - \frac{1}{2}m^2 + m_0^2, \\ m_3^2 &= B\mu. \end{aligned} \quad (7)$$

where we have indicated by " $D$ -terms" the usual  $D$ -terms coming from  $SU(2) \otimes U(1)$  and  $m_0^2$  denotes the supersymmetry soft-breaking terms coming from supergravity,  $m_0^2 \sim \epsilon m^2$ . A novel feature of this model is that the field  $H_u^0$  gets vacuum expectation value (VEV) already at the tree level since  $m_{H_u}^2$  is negative at high scales. Since  $B$  is not generated at order  $\epsilon$ , to get the correct value of  $M_Z^2$  at the weak scale requires  $m$  of the order of a few hundred GeV or less. It is then clear that there is a potential conflict between the desirable value of  $\langle H_u^0 \rangle$  and the above prediction for the gaugino mass unless we choose a sufficient large coupling  $\lambda'$ . Furthermore, we do expect the renormalization group equations to reduce the  $m_{H_u}^2$  as we go down to the weak scale from the Planck scale. In any case, this model would lean more towards a larger  $\tan\beta$  sector of the MSSM. In the second model that we present, the VEV of  $H_u^0$  arises purely from radiative corrections due to its different  $U(1)$  charge assignment and no such constraint on  $\tan\beta$  or  $\lambda'$  follow.

We also notice that a VEV of order of  $\frac{v_d v_u}{M_{Pl}}$  is induced for the field  $\phi_+$  when taking into account supergravity effects.

Let us now look at other parameters of the theory. It is clear from the Eq. (1) that  $A_u \sim \epsilon m$  whereas  $A_d = 0$  to order  $\epsilon$ . In fact including the higher order terms in the superpotential and the Kahler potential it is easy to see that  $A_d \sim \epsilon^2 m$  (while  $B\mu \sim \epsilon^{3/2} m^2$ ). Note however that these are the values at the Planck scale and they will evolve to higher values at the weak scale. It is however important to note that both the values of  $A$  and  $B$  remain of order  $\epsilon$  at most since the value of  $B$  at weak scale is proportional to  $m_{\lambda_g}$  times the renormalization logarithm factor and similarly for  $A$ . Finally we note that the second term in the superpotential  $W_2$  is the one responsible for the down quark and charged lepton masses. Substituting the VEV's for the  $\phi_-$  field, it is easy to see that there is an automatic suppression of  $\epsilon$  in the down quark and charged lepton Yukawa couplings. If one chooses  $h_{d,e}$  of the same order as the up quark couplings, then this will explain why  $m_{d_i, e_i} \ll m_{u_i}$ , a property shared by the second and the third generation fermions.

### *Flavor Changing Neutral Current Effects*

Let us now discuss the FCNC effects in this model. To study this, we note that squark masses  $m_q^2$  (both left and right handed types) receive two contributions: a universal contribution from the  $D$ -term which is of order  $m^2$  and a non-universal contribution from the supergravity Kahler potential of order  $F_{\phi_+}^2/M_{Pl}^2 \equiv \epsilon m^2$ . As both these contributions are extrapolated from the Planck scale down to the weak scale the pattern of the first two generation squark masses remain practically unchanged whereas the masses of the stop receive significant contributions. It was noted in [2] that in order to satisfy the present observations of FCNC effects (such as  $K^0 - \bar{K}^0$  mixing), the mixings between the  $\tilde{s}$  and the  $\tilde{d}$  squarks (i.e.  $m_{\tilde{s}\tilde{d}}^2$ ) in the flavor basis or the squark mass differences between the first two generations in the mass basis must satisfy a stringent constraint. In the flavor basis,

it is given by (see Dugan et al., in [2]),  $\text{Im}\left(\frac{m_{\tilde{s}\tilde{d}}^4}{m_{\tilde{q}}^4}\right) \leq 6 \times 10^{-8} \frac{m_{\tilde{q}}^2}{m_W^2}$ . We have assumed the phases in our model to be arbitrary; therefore the most stringent constraint comes from the CP-violating part of the  $K^0 - \bar{K}^0$  mass matrix. In our model,  $m_{\tilde{s}\tilde{d}}^2$  arises purely from the supergravity effects are of order  $\sim \epsilon m^2$  and the above FCNC constraint is satisfied if  $\epsilon \simeq 10^{-2}$  or so. Thus our model confirms the conjecture of Ref. [4].

#### *Electric dipole moment of the neutron*

The electric dipole moment of the neutron  $d_n^e$  in supersymmetric models have been discussed in several papers [7] and it is by now well-known that the gluino intermediate states in the loop graph contributing to the  $d_n^e$  gives a contribution which is some three orders of magnitude larger than the present experimental upper limit for generic values of the parameters. The situation is different in our model since we see that a number of parameters of the model such as the gluino masses, the  $A$  and  $B$  are down by powers of  $\epsilon$ . In order to see the impact of this on the NEDM, we will again consider the charge assignment for the first model where the Kahler potential induced mass splittings in the squark masses are of order  $\epsilon m^2$ . For the gluino contribution, we borrow from the calculation of Kizukuri and Oshimo [7], which gives:

$$d_n^e = \frac{2e\alpha_s}{3\pi} (\sin \alpha_u A_u - \sin \theta_\mu \cot \beta |\mu|) \times \frac{m_u}{m_{\tilde{q}}^2} \frac{1}{m_{\lambda_3}} I\left(\frac{m_{\tilde{q}}^2}{m_{\lambda_3}^2}\right), \quad (8)$$

where  $\alpha_u = \theta_{A_u} - \theta_{\lambda_3}$  is the difference between the phases of the  $A$ -term and the gluino mass. We have kept only the up quark contribution since in our model  $A_d \ll A_u$ ;  $m_{\tilde{q}}$  denotes the mass of the heavier of the two eigenstates. Since in this model,  $m_{\lambda_3} \simeq \sqrt{\epsilon} m$  and  $m_{\tilde{q}} \simeq m$ , one finds that  $I \simeq \epsilon$ . This leads to  $d_n^e \simeq \frac{2\alpha_s}{3\pi} \epsilon^{3/2} \frac{m_u}{m^2}$ . Here we have used the fact that  $A \sim \epsilon m$ ;  $\mu \sim \sqrt{\epsilon} m$ . For  $\epsilon \simeq 10^{-2}$ , this gives an additional suppression of  $10^{-3}$  over the prediction of generic parameter values of the MSSM as required.

We wish to point out that the above suppression depends on the fact that  $Q_1, u_1^c, d_1^c$  all

have nonzero  $U(1)$  charge. If on the other hand,  $d^c$  and  $u^c$  had zero charge, their dominant mass would come from the supergravity effect and, as a result,  $m_{d^c}^2 \sim m_{u^c}^2 \simeq \epsilon m^2$ . The the above gluino contribution to  $d_n^e$  would then be less suppressed (by a factor  $\sqrt{\epsilon}$  rather than  $\epsilon^{3/2}$ ).

*A second model:*

We next present an alternative charge assignment which qualitatively explains the observed mass hierarchy of quarks while keeping all other  $\epsilon$ -suppressions of the various parameters of the model unchanged. We choose  $Q_3$ ,  $u_3^c$  and  $H_u$  to have zero  $U(1)$  charge, but all other quarks have charge  $+1$  as does  $H_d$ . This charge assignment for the  $H_{u,d}$  allows the Kahler potential term  $K_1$  in Eq. (2) so that the suppression of the  $\mu$ -term is maintained as in the first model. Moreover, only the Yukawa coupling  $Q_3 H_u u_3^c$  is allowed without any suppression from the  $\epsilon$  factor explaining why the top quark has large mass [8]. On the other hand, the other Yukawa couplings are suppressed with powers of  $\epsilon$  qualitatively explaining why their masses are so much smaller than the top quark mass. The superpotential for such a theory can be written as:

$$\begin{aligned} & h_{33} Q_3 H_u u_3^c + h'_{3a} Q_3 H_d d_a^c \frac{\phi_-^2}{M_{P\ell}} + h_{3j} Q_3 H_u u_j^c \frac{\phi_-}{M_{P\ell}} \\ & + h_{ij} Q_i H_u u_j^c \frac{\phi_-^2}{M_{P\ell}^2} + h'_{ij} Q_i H_d d_j^c \frac{\phi_-^3}{M_{P\ell}} \end{aligned} \quad (9)$$

where  $i, j$  go over 1, 2 and  $a$  goes over 1, 2 and 3 and are generation indices. They lead to the following kind of up and down quark mass matrices.

$$M_u = m_1 \begin{pmatrix} \epsilon & \epsilon & \sqrt{\epsilon} \\ \epsilon & \epsilon & \sqrt{\epsilon} \\ \sqrt{\epsilon} & \sqrt{\epsilon} & 1 \end{pmatrix} \quad (10)$$

and

$$M_d = m_2 \begin{pmatrix} \epsilon^{3/2} & \epsilon^{3/2} & \epsilon \\ \epsilon^{3/2} & \epsilon^{3/2} & \epsilon \\ \epsilon & \epsilon & \epsilon \end{pmatrix}. \quad (11)$$

where  $m_{1,2}$  are mass parameters related to the  $v_{u,d}$  and the Yukawa couplings. This pattern predicts that  $m_u = 0$  and  $m_c \simeq \epsilon m_t$ . In the down sector,  $m_b \simeq \epsilon m_t$ ,  $m_s \simeq \sqrt{\epsilon} m_b$  and  $m_d = 0$ , which for  $\epsilon \simeq 10^{-2}$  roughly corresponds to observations. Similar considerations can be applied to the leptons. Other than to note this qualitatively interesting prediction, we do not want to pursue the detailed predictions of this model for fermion masses and mixings here. However, we want to point out an interesting feature of the model that  $H_u$  VEV arises purely from radiative corrections (and not at the tree level as the first class of models) and is therefore not locked to the value of  $m$ . As far as the  $A$ -term is concerned, it is clearly suppressed by powers of  $\epsilon$  which depend on then generation indices; for instance,  $A_{33}^u = \epsilon m$ ,  $A_{3a}^d = \epsilon^{3/2} m$  and so on. In this case the  $d_n^e$  is more highly suppressed than the first model.

A few comments are in order regarding various aspects of the model:

- (i) The low energy effective theory contains all fields except the  $\phi_-$  and all components of the field  $\phi_+$  have masses of order  $m$  and they do not mix with the other Higgs fields even though the  $U(1)$  symmetry is broken.
- (ii) Different versions of our theory with other charge assignments are possible. But one has to be careful not to assign negative  $U(1)$  charges to the quarks or leptons since that will lead to breaking of color and electric charge.
- (iii) The gravitino mass in this model is of the order of  $\sqrt{\epsilon} v_u v_d m / M_{Pl}^2$  or less and it arises once the  $\phi_+$  field acquires a VEV due to supergravity effects.
- (iv) The model has the feature that one can choose the Kahler potential and the superpotential with arbitrary number of higher dimensional terms as long they are  $U(1)$

invariant and yet our results will remain unchanged. The higher order terms induce small corrections down by higher powers in  $\epsilon$ .

In conclusion, we have demonstrated with two examples that it is possible to construct interesting realistic supersymmetric models of quarks and leptons using the idea that an anomalous  $U(1)$  gauge symmetry is responsible for generating supersymmetry breakdown. These models have the additional attractive feature that they solve several fine tuning problems of the MSSM associated with FCNC effects and electric dipole moment of the neutron. They also give desirable values for the  $A$ , the  $B$  and the  $\mu$  parameters and also have the potential to qualitatively explain fermion mass hierarchies.

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